

A STUDY OF THE NOISE RADIATION FROM
FOUR HELICOPTER ROTOR BLADES

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SUMMARY

Acoustic measurements were taken of a modern helicopter rotor with four blade-tip shapes in the NASA Ames 40-by-80-Foot Wind Tunnel. The four tip shapes are: rectangular, swept, trapezoidal, and swept-tapered in planform. Acoustic effects due to tip shape changes were studied based on the dBA level, peak noise pressure, and subjective rating. The swept-tapered blade was found to be the quietest above an advancing tip Mach number of about 0.9, and the swept blade was the quietest at low speed. The measured high-speed impulsive noise was compared with theoretical predictions based on thickness effects; good agreement was found.

INTRODUCTION

The helicopter rotor blade tip region is one of the most important sources of helicopter noise, and the effects of shaping the tip on the noise generation are complicated because of the many phenomena involved in the tip aerodynamics. For different tip shapes, the blade aerodynamic loading distributions and the resulting tip vortices are different. Due to the combined effects of tip vortex changes and different aerodynamic response at the tip region, the blade/vortex interaction noise will be changed. Because of the change in unsteady blade loading, the rotational noise radiation will also be changed. At high speed, blade thickness can be a significant noise source (refs. 1-4). The thickness noise is directly related to the tip planforms and to their thickness distributions. Noise will also be generated when the tip region experiences strong compressibility effect (ref. 5), which is closely related to blade tip shapes.

Because of the complexity of the tip-shape effects on rotor noise generation, no complete analytical method has been developed. Lyon, Mark, and Pyle (ref. 6) conducted a theoretical study of the rotor tip sound radiation and tried to synthesize rotor tips for less noise. Lawson, Whatmore, and Whitfield (ref. 7) found that cutting off one corner of

rectangular fan tips can significantly reduce the high frequency broadband noise. Farassat and Brown (ref. 2) and Farassat (ref. 8) found, in a theoretical study, that airfoil thickness distribution and planform sweep of the blade tip region have significant effects on noise radiation. Since theoretical predictions cannot completely determine the acoustic effects of tip shapes, experiments have been performed to evaluate several tip shapes, either in a wind tunnel or in flight. Recently, a full-scale, ogee-tip helicopter rotor was tested on a whirl tower and in flight (ref. 9). Favorable effects on acoustics, performance, and loads were found.

It is expected, therefore, that suitable design of rotor tip shapes could reduce noise and improve performance. To investigate this possibility, a wind-tunnel experiment was conducted using a modern helicopter rotor, 13.4-m in diameter, with interchangeable tips. The rotor test encompassed an advance ratio range of 0.2 to 0.375 and an advancing tip Mach number range of 0.72 to 0.97. Four tip shapes were tested. The test data were used to determine the acoustic effects of the specific tip shapes and to establish a data base for theoretical modeling and predictions of high-speed rotor impulsive noise.

SYMBOLS

C_{LR}/σ	lift coefficient to solidity ratio
$M_{1,0}$	blade rotational tip Mach number
$M_{1,90}$	blade advancing tip Mach number
P	acoustical pressure, N/m^2
V	wind-tunnel speed, m/sec
α_s	rotor shaft angle, deg
ΩR	blade rotational tip speed, m/sec

EXPERIMENT

A 13.4-m-diameter, four-bladed rotor with interchangeable tips constructed by Sikorsky Aircraft was tested in the NASA-Ames 40-by 80-Foot Wind Tunnel. Four different tip shapes were tested (fig. 1). The tip shapes are: rectangular, swept, tapered (trapezoidal), and swept-tapered. The rectangular tip serves as a baseline; the other three tips were used to systematically evaluate the effects of taper and sweep. The rotor blades had a constant chord and 9.5% thickness ratio airfoil inboard of 95% radius. The rectangular tip maintained the constant chord and thickness out to 100% radius. The trapezoidal tip was tapered to 60% of the baseline chord at the tip, with a constant thickness ratio and an unswept quarter chord line. The swept tip had constant

chord and thickness with 20° sweepback. The swept-tapered tip had 35° sweep of the leading edge, a 10° sweep of the trailing edge, and a constant thickness ratio.

The investigation covered a wide range of operating conditions. The range of advancing tip Mach number was 0.72 to 0.96, and the advance ratios were from 0.2 to 0.375. The rotor performance is given in reference 10.

Seven 13-mm (1/2-in.) B & K condenser microphones with cathode followers were used for the acoustical measurements. Each microphone was equipped with a nose cone to reduce the wind-induced noise. The microphone locations are given in table 1 and shown in figure 2. The microphones were calibrated daily with a B & K pistonphone. Conventional acoustic power supply and amplifier units were used for data conditioning. The acoustical signals as well as 1/rev and 256/rev voltage pulses were recorded on an Ampex 1300A, 14-track FM tape recorder. The recorder setting was IRIG wide-band 1 and 19.05 cm/sec (7.5 ips), with a center frequency of 27 kHz, and a bandwidth of 5 kHz. An acoustical polarity calibration device, which generated a strong positive pressure pulse, was used to calibrate the polarity of the acoustical data system.

The A-weighted SPL was obtained by using a B & K audio frequency analyzer, type 2107. The acoustical waveforms were reduced by a minicomputer-based time series analyzer. The noise signal was sampled at a rate of 5120/sec for 0.2 sec, beginning with the trigger of 1/rev pulses. The resulting frequency resolution was 5 Hz with a Nyquist frequency of 2.56 kHz. A 2 kHz anti-aliasing filter was used. By averaging 50 records in a synchronized fashion, the nonperiodic noise was significantly reduced. A discrete Fourier transform was then applied to obtain the amplitude and phase relationship of each frequency component. By zeroing out the frequency components below 25 Hz and applying inverse Fourier transform, an averaged, 25 Hz high-passed, phase distortion-free acoustical waveform was obtained. These waveforms are particularly useful in the study of helicopter impulsive noise. A complete set of noise waveforms is given in reference 11.

EXPERIMENTAL RESULTS

dBa Levels

The acoustical data measured in the wind tunnel were contaminated by the background noise and reverberations. The background noise data were measured at various wind-tunnel speeds with the rotor hub turning (without blades). The A-weighted SPL of background noise is proportional to the 5.6th power of the wind-tunnel velocity. The A-weighted SPL of rotor noise was corrected for the background noise. These corrected dBA quantities should not be considered to be the absolute values because of reverberations from the hard wind-tunnel walls. Nevertheless, these data are useful for comparisons of the different tip shapes.

Figure 3 shows the dBA noise levels of Mic (microphone) 3 as a function of C_{LR}/σ , for the rotor operating at $V/\Omega R = 0.2$, $M_{1,0} = 0.6$, and $\alpha_s = -5^\circ$. No data for the trapezoidal tip are available at these conditions. The noise of the swept blade is about 2 dBA lower than that of the rectangular blade or swept-tapered blade over most of the range of blade loading. The difference is small at high blade loading. Figure 4 shows the noise level of Mic 3 at $V/\Omega R = 0.375$, $M_{1,0} = 0.65$ and $\alpha_s = -5^\circ$. The dBA levels of swept blades are the lowest, with the swept-tapered blades second. The rectangular blade and trapezoidal blades are loudest. Similar trends were observed at Mic 6.

The advancing tip Mach number is an important parameter defining the rotor noise. Figure 5 shows the noise levels of the four blades over a Mach number range. Below about $M_{1,90} = 0.9$ the swept blades have the lowest dBA. When the advancing tip Mach number is above 0.9, the swept-tapered blades have the lowest dBA. Similar trends were found at Mic 6.

Waveforms

The noise waveforms may be more useful in studying the rotor noise when impulsive components are dominant. The noise waveforms in the different stages of data reduction are shown in figure 6. The background noise and rotor broadband noise are reduced or eliminated by averaging 50 times, as seen in figure 6(b). The 25 Hz high-pass filtering mainly eliminated the first blade passage harmonic of the thrust- and drag-generated rotational noise. The averaged and filtered waveforms are useful in the study of rotor impulsive noise. Although the tunnel background noise and rotor broadband noise can be averaged out, the reflected noise from the tunnel surfaces are still present in the processed waveforms. However, if the time lag of reflections is larger than the incident pulse width, the reflections will not mask the impulsive noise. For the test configuration considered here, it was verified experimentally that the first reflection (from the wind-tunnel floor) arrives about 4 msec after the direct wave. The sound pressure pulse width was found to be much less than 4 msec, particularly at high speed. Actually, there was little evidence of impulsive noise reflections in the measured sound pressure signal (see fig. 6). A probable factor in the absence of strong reflections is the location of the microphone (Mic 3) nearly in the rotor tip-path plane, where the impulsive noise directivity is greatest. The pulse reflected off the tunnel floor or ceiling thus has much smaller magnitude than the pulse traveling directly from the rotor to the microphone.

Figure 7 shows the acoustical waveforms (averaged 50 times) of the four tips at $V/\Omega R = 0.375$, $M_{1,0} = 0.65$ ($M_{1,90} = 0.90$), and $\alpha_s = -5^\circ$. The swept-tapered tip blades produce the lowest impulsive noise. This is also true for the advancing Mach number greater than 0.90. However, the dBA results of figure 5 show the swept tip blade to be the lowest among four tip shapes at $M_{1,90} = 0.90$. This is because dBA is an overall rating of noise with an emphasis on the high frequencies (around 3 kHz); rotor noise contains many components in addition to impulsive noise. At high advancing tip Mach number, both the dBA and impulse peak indicate the swept-tapered tip blades are quietest.

Subjective Rating of High Speed Impulsive Noise

Subjective rating of rotor high-speed impulsive noise (with its complicated waveform) cannot be immediately discerned based on dBA measurements of the noise. An ordering based on dBA measurements will not necessarily agree with an ordering based on peak pressure levels. To find subjective ratings of the four blade sets of this investigation, a subjective evaluation was conducted.

Twenty subjects were used for this test. Each subject was presented with the noise from a pair of rotors, first one and then the other, separated by a 3-sec gap. Ten seconds later, another pair was presented. All possible pairs were thus presented (in scrambled order) and the subjects were asked to judge which of the two rotors of each pair was loudest.

For all samples, the advance ratio was 0.375, the rotational Mach number was 0.65 (corresponding to an advancing tip Mach number of 0.90), and C_{LR}/σ was 0.07. Recordings from Mic 3 were used. The recordings were played back to the subjects in an anechoic chamber. The recordings were band-pass filtered from 25 Hz to 2.5 kHz, and played to the subjects at a reduced but constant level. The physical measurements of the original signals are shown in table 2.

A subjective ordering of the loudness of the different rotor tips presented can be derived from the frequencies with which the various tip shapes were judged loudest. The rectangular tip was judged loudest the most often, followed by the swept tip, then the trapezoidal tip. The swept-tapered tip was judged loudest the least often (see table 2). A standard statistical test (t-test) showed that the differences in responses between different tip shapes was significant for all pairs except between the trapezoidal tip and swept-tapered tip.

The ordering derived from the subjects' responses agrees with the ordering derived from the peak negative impulses but not the ordering from the dBA measurements. This indicates that when this impulse is presented in the rotor noise, perception of loudness correlated more with impulsive peak level than with the dBA level of the noise. It should not, however, be assumed that the peak level of impulsive noise is the only relevant factor determining subjective loudness. More extensive testing would have to be done to determine precisely what affects subjective loudness.

COMPARISON OF MEASURED IMPULSIVE NOISE WITH THEORY

Time histories of the measured impulsive noise are shown in figure 8 for the trapezoidal tips, at three advancing tip Mach numbers. The negative pressure pulse increases in amplitude with Mach number so that it dominates the sound pressure signal at high speed. At very high speeds a positive pressure spike closely follows the negative pulse. Similar results were found from flight measurement of a UH-1 helicopter noise (ref. 12). Calculations were made based on the thickness noise theory which was developed by

Johnson (ref. 13). Calculations based on the theory of Farassat and Brown (ref. 2) or the theory of Schmitz and Yu (ref. 3) can result in similar predictions. There is more to the periodic rotor noise than just the thickness noise component, but the impulse is well accounted for by the thickness noise theory. More comparisons can be found in reference 4.

Figure 9 compares the measured and calculated peak impulsive noise pressure for four different blades over the range of advancing tip Mach number. The advance ratio is 0.375 for all cases. The overall correlation is quite good. It can be seen that the impulsive noise can be reduced by the cross-sectional area of the blade tip. Sweeping the blade tip without changing the chord or thickness has little effect on the thickness noise. Figure 10 shows the directivity in the elevation plane for the swept-tapered rotor at an advancing tip Mach number of 0.90. As can be seen, the impulsive noise is quite directional. Good agreement between the experimental data and calculation is found.

CONCLUSIONS

The acoustic data of a 13.4-m rotor with four blade-tip shapes were obtained in a wind-tunnel test. These tip shapes are rectangular, swept, trapezoidal (tapered), and swept-tapered. Below an advancing tip Mach number of about 0.9, the dBA data appear to indicate that the swept tip is the quietest, the swept-tapered tip second, the trapezoidal tip third, and the rectangular tip the most noisy. Above an advancing tip Mach number of about 0.9, a distinct negative acoustical pulse, which occurs once per blade passage, was observed. The amplitudes of these pulses are strongly dependent on the advancing tip Mach number. Based on the amplitude of impulsive noise, the data indicate the swept-tapered tip is the quietest, the trapezoidal tip second, the swept tip third, and the rectangular tip loudest.

The overall comparisons show good agreement between measured impulsive noise and calculated results based on thickness noise theory. This correlation suggests that the rotor high-speed impulsive noise is thickness noise dominated. Changing blade chord or thickness has significant effects on the noise radiation. Simply sweeping alone has little effect on high-speed impulsive noise. A complete prediction of helicopter noise will, of course, require an accurate treatment of all noise components.

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TABLE 1. - MICROPHONE LOCATIONS

Mic. no.	X		Y		Z		Above floor		Angle below horizontal plane, deg
	m	ft	m	ft	m	ft	m	ft	
1	-19.8	-65	0.61	2	5.30	-17.4	1.22	4	15
2	-2.65	-8.7	1.89	6.2	3.08	-10.1	3.02	9.9	43.6
3	-19.2	-63	0	0	4.21	-13.8	2.29	7.5	12.4
4	-18.6	-61	0.61	-2	2.62	-8.6	3.90	12.8	8
5	-19.0	-62.3	5.5	18.2	4.18	-13.7	2.35	7.7	11.9
6	-3.47	-11.4	3.60	11.8	3.90	-12.8	2.19	7.2	38
7	-19.0	-62.3	5.55	-18.2	4.18	-13.7	2.35	7.7	11.9

TABLE 2. - RATINGS OF IMPULSIVE ROTOR NOISE

	Rectangular		Swept	Trapezoidal		Swept-tapered
	117.2	115.1		116.7	115.9	
dBA	90	70		60	50	
Peak pressure, N/m^2	180	177		177	180	
Possible number of responses	153	107		51	46	
Number of times judged louder						

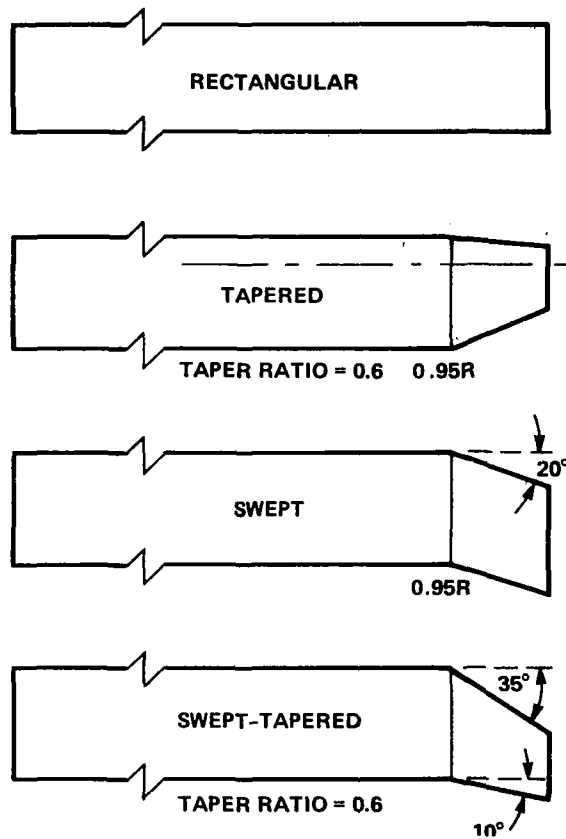


Figure 1.- Four tip shapes tested.

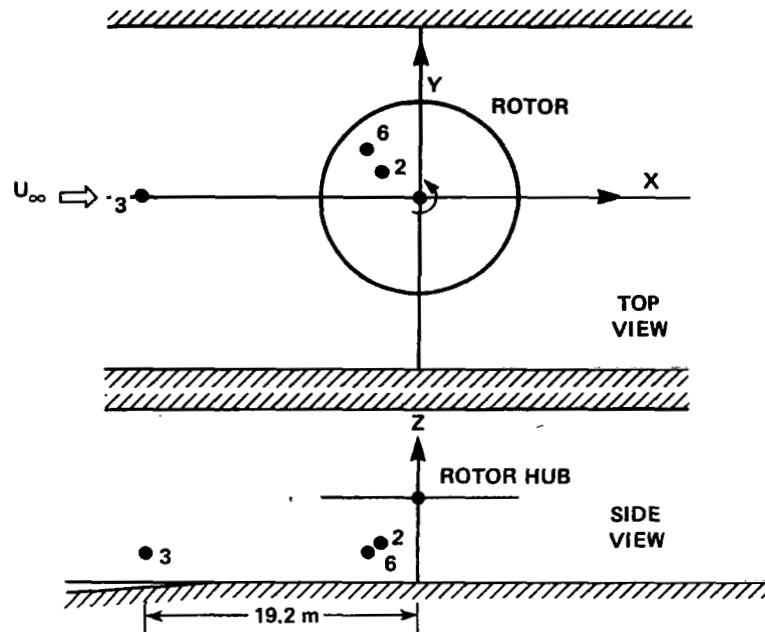


Figure 2.- Microphone locations.

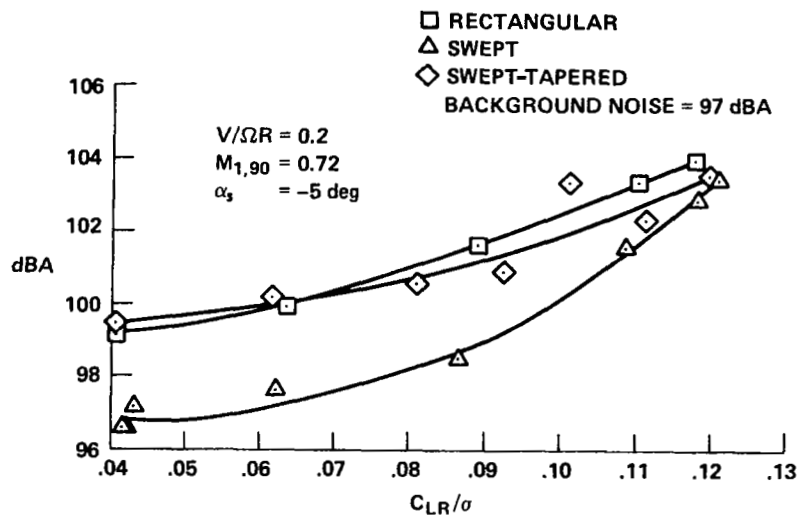


Figure 3.- dBA noise levels as a function of C_{LR}/σ .
 Mic 3; $\alpha_s = -5^\circ$; $V/\Omega R = 0.2$; $M_{1,90} = 0.72$.

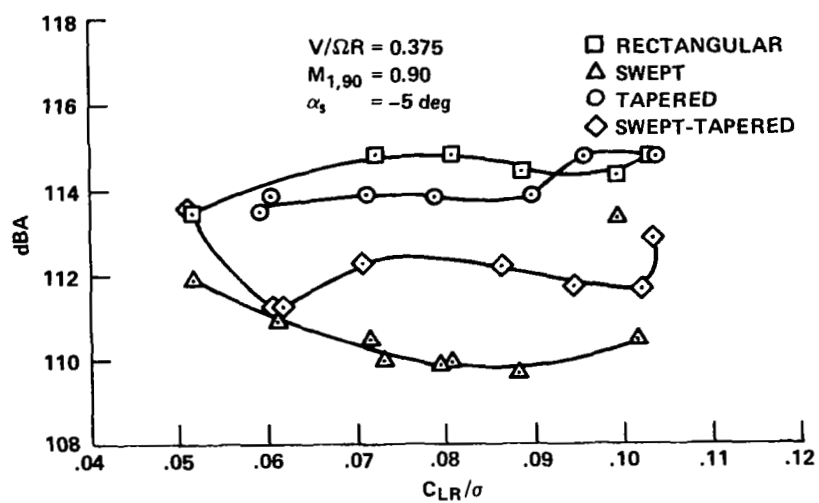


Figure 4.- dBA noise levels as a function of C_{LR}/σ .
 Mic 3; $\alpha_s = -5^\circ$; $V/\Omega R = 0.375$; $M_{1,90} = 0.9$.

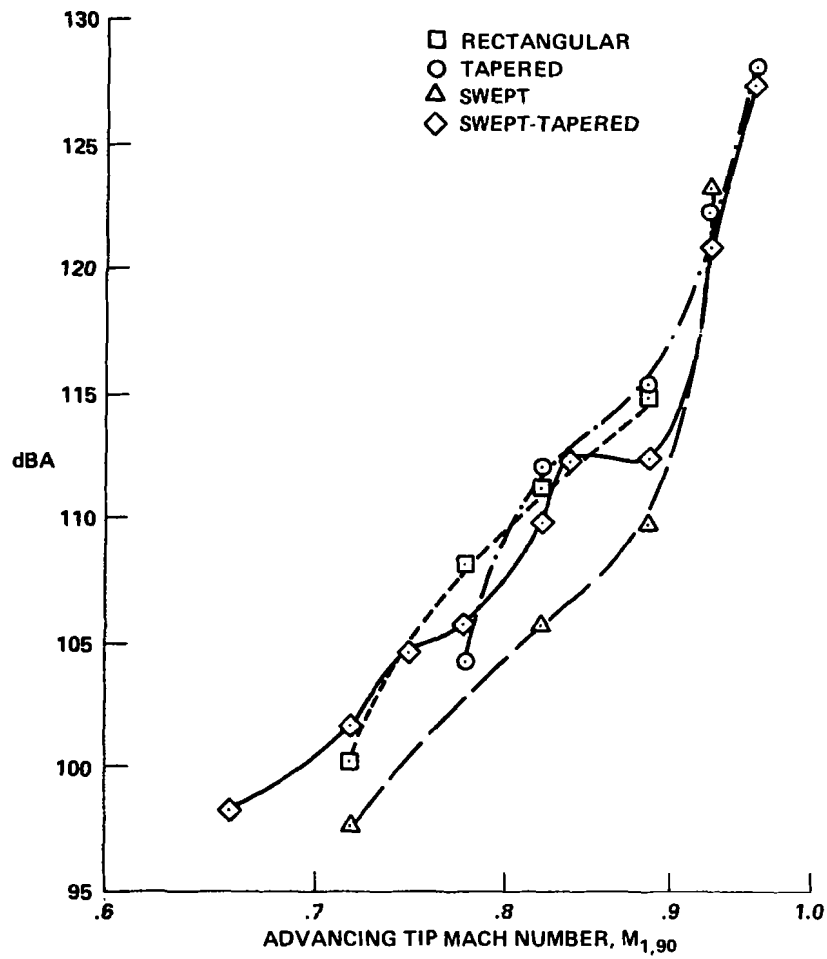


Figure 5.- The effect of Mach number on dBA level.
 Mic 3; $C_{LR}/\sigma = 0.07$; $\alpha_s = -5^\circ$.

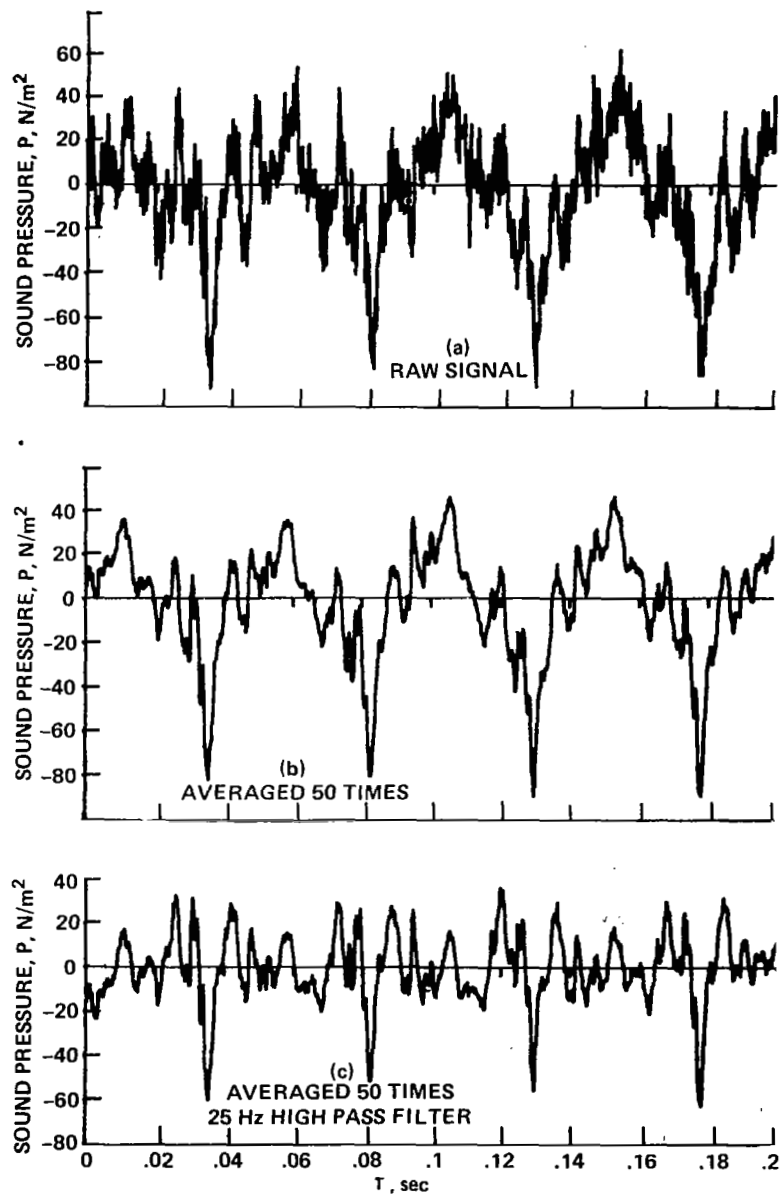


Figure 6.- Example of the noise signal processing.
Trapezoidal tips; $M_{1,90} = 0.9$; $V/\Omega R = 0.375$.

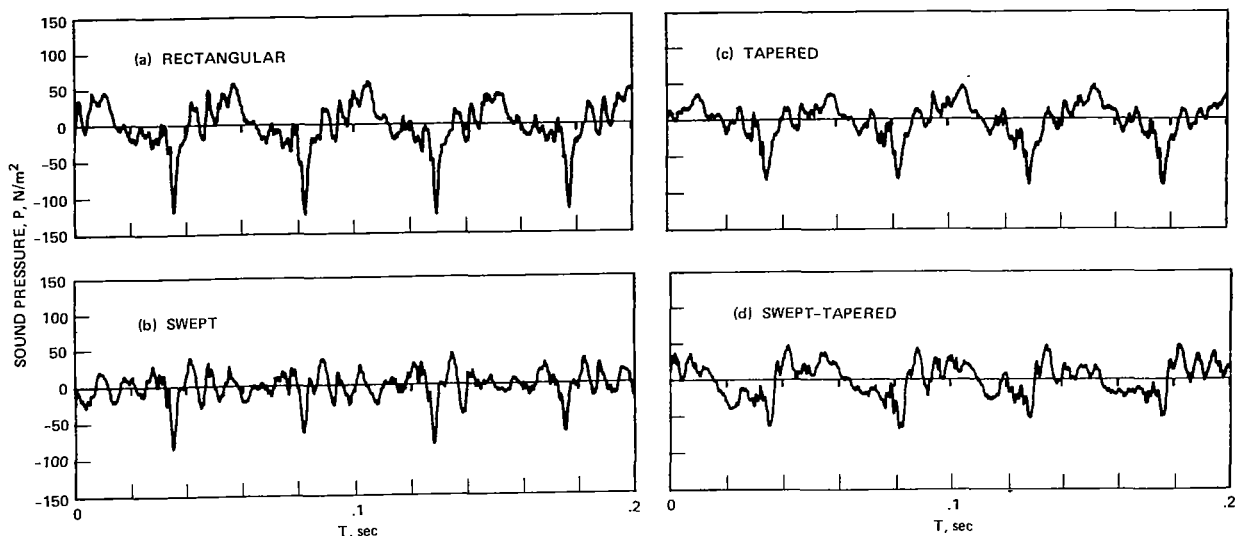


Figure 7.- Waveforms of four blades. $V/\Omega R = 0.375$;
 $M_{1,0} = 0.65$; $M_{1,90} = 0.9$; $\alpha_s = -5^\circ$.

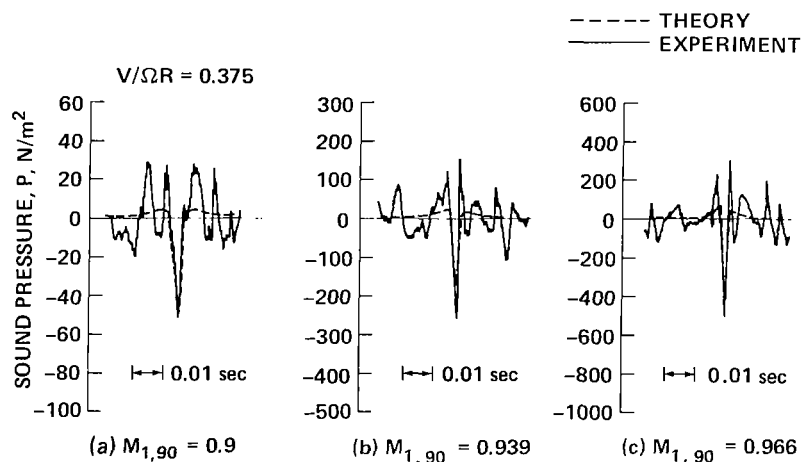


Figure 8.- Comparison of measured and calculated thickness noise time histories at several advancing tip Mach numbers. Trapezoidal tips; $V/\Omega R = 0.375$.

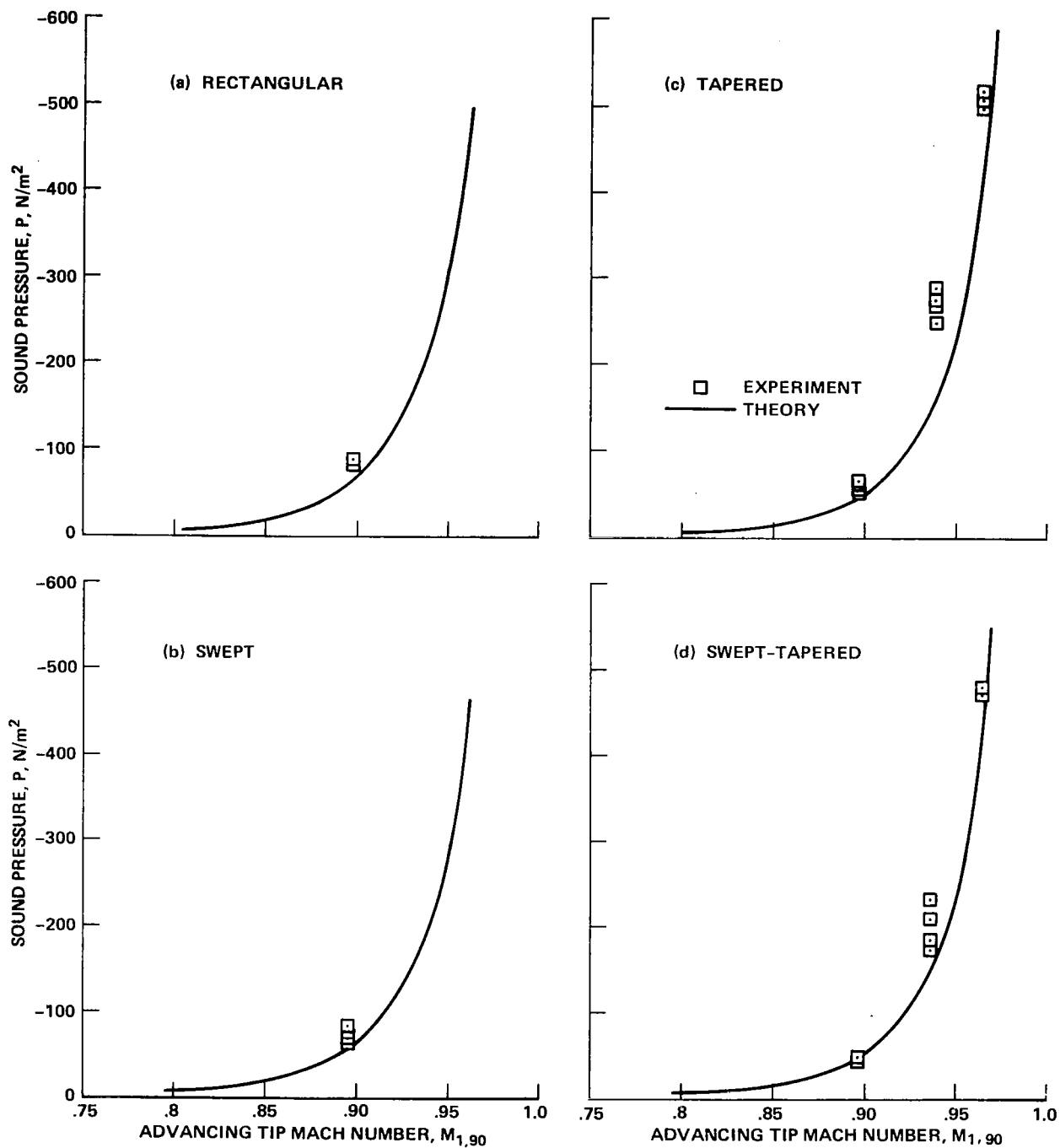


Figure 9.- Comparison of measured and calculated impulsive noise peak pressures. $V/\Omega R = 0.375$.

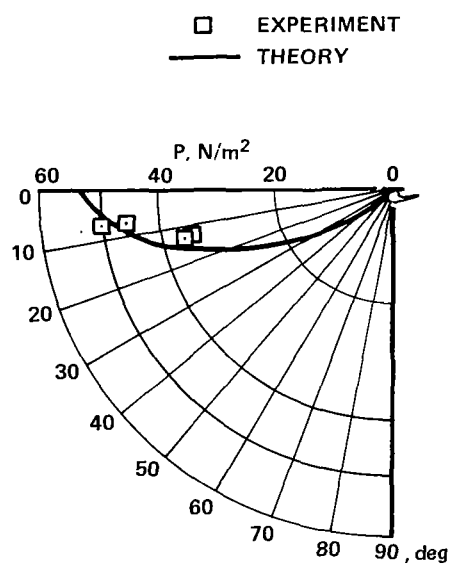


Figure 10.- Impulsive noise peak pressure in the vertical plane forward of the rotor disk. $V/\Omega R = 0.375$; $M_{1,0} = 0.65$; $M_{1,90} = 0.90$.